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An Experimental and Numerical Study of the Effects of Design Parameters on Water Mist Suppression of Liquid Pool Fires

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13. ABSTRACT (*Maximum 200 words*)

This report presents the results of an experimental and numerical parametric study of water mist suppression of liquid pool fires. The numerical part was conducted with small 2-D methanol pool fire, while the experiments were conducted with a 50 cm diameter pan heptane and JP-8 pool fires. Analyses of results of the experimental and numerical parts lead to similar conclusions. First, the results show that base injection of droplets enhanced their suppression effectiveness by as much as two times compared to top injection. This is because the droplets evaporated within the lower region of the fire where a greater effect of oxygen dilution and water vapor higher heat capacity is fully realized. Secondly, the experimental results show that smaller droplets are more effective than larger droplets in both top and base injections. The similarity between the model predictions and the experimental data indicates that the results of the parametric study conducted with a small scale laminar pool fire can be useful in the design of water mist suppression systems for large scale fires. Finally, the experimental results show that water mist is more effective in suppressing JP8 fires than heptane fires. It is concluded that the difference in effectiveness is largely due to the additional effects of surface cooling.

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1.0 INTRODUCTION

The use of water mist as a rapid fire extinguishing agent is receiving considerable attention lately since the production of halon 1301 was banned in 1994. Water mist is a contending alternative to halon 1301 especially in total flooding applications. Although water mist systems require minutes to extinguish fires, while some of the contending gaseous agents require seconds, it has been shown [1-3] that water mist will dramatically lower the temperature of the fire compartment such that manual intervention is easily carried out. Furthermore, water mist systems use much less water than conventional sprinkler systems to achieve the same level of effectiveness. With the temperature of the compartment considerably lowered, and since water is non-toxic, the man-hours required to restore the compartment to use is considerably reduced. This fits well with the current mandate in the Navy to reduce manning in the ships of the 21st century.

The Navy is also spending considerable effort in developing fire retardant composite materials for use in future ships. It has been reported that composite materials have potential use in virtually everywhere in ships and submarines [4]. An example of a new fire retardant composite material is the phthalonitrile resin system developed by Keller [5]. Such materials resist fire propagation by forming char which is a heat barrier between the flame and the pyrolyzing virgin material. Most gaseous fire suppressing agents can extinguish the flame on any materials faster than water mist. However, with such fire retardant material, the char holds a lot of heat even after the flame has been extinguished. Thus pyrolyzates can still be produced within the solid and these readily ignite when the oxygen concentration builds back up. With water mist as the extinguishing agent, the char layer is cooled directly by droplets evaporating on it before or after the flame is extinguished. Thus the production of pyrolyzates is suppressed and re-ignition is avoided.

To achieve optimum use of water mist system, there is need to understand the various phenomena involved in the interaction of the water mist spray and the fire gases. First, there is the droplet motion through an opposing turbulent fire flow. Traditionally, water is injected from the top. Then, there are the transport processes between the moving cold droplets and the hot fire gases. The resulting evaporation of the droplet can be gradual (from the droplet surface) or instantaneous where the entire droplet attains the boiling point at the same time. As the droplets evaporate in the combustion zone the water vapor dilutes the oxygen concentration and absorbs additional sensible heat to be heated up to the fire temperature. The net effect of these processes is the reduction in combustion rate and in gas temperatures (gas phase cooling). Some of the droplets may survive as they pass through the hot combustion region and eventually reach the condensed fuel surface which is either a liquid pool or a pyrolyzing/charring solid surface. The droplets finally absorb latent heat from the surface to evaporate completely. This cools the surface, thereby reducing the gaseous fuel production rate (burning rate).

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Very few studies have addressed in detail the interaction of water spray with fires [6-12]. Alpert [6] developed a field model to predict the penetration of a sprinkler spray through the plume of a burning object. The model essentially combines a model of a 2-D flow produced by a heated jet (or ordinary heat source) and a water spray model. Later, Bill [7] verified this model using the Factory Mutual Research Corporation's actual delivered density (ADD) apparatus. Their results show some good agreement between the predicted and measured density of water reaching the base of a heptane spray fire when the sprinkler nozzles are located 3.05m and 4.57m above the base.

Hoffman and Galea [8] developed another field model of a compartment fire with the sprinkler turned on. The predictions of the model were later verified with experimental data for (a) a corner fire in an office-size compartment and (b) a bed fire in a large hospital room [9]. The temperature predictions in both cases were (qualitatively) in good agreement with experimental results.

Prasad et al. [10-12] developed a numerical model to study the interaction of water mist spray and a small laminar 2-D diffusion flame. The model combined a fire model and a spray model to predicted temperature and species profiles in the suppressed flame . The temperature predictions were verified by experimental data for both methane and methanol diffusion flames. Later, a parametric study [13] was undertaken where the droplet size, velocity, number density, spray orientation (base, top or side) and spray angle were varied. The results of this study depict the combination of the various parameters for optimum suppression in fire heat release rate. A summary of this theoretical optimization study will be presented in this paper and the similarity between the results of this study and the results of the present large scale experiments will be discussed.

Most large scale water mist fire suppression experiments were with enclosed fires [e.g., 1,3,14]. Tests with large scale fires in the open are few [15,16]. Downie et.al [15] studied the suppression of a large methane fire subjected to a steady water mist spray from a single hollow cone nozzle mounted above the fire. The large plume to flame thrust ratio in their experiment resulted in negligible direct penetration of the droplets into the fire region. Their result shows a significant reduction in oxygen concentration and increase in carbon monoxide concentration inside the flame when the mist was applied. Takahashi [16] studied the extinquishment of plastic fires with water spray. He compared the extinquishment times with plain water and 'wet' water. Wet water is foam agent diluted 10,000-fold with water. He showed that wet water reduced the extinquishment time by as much as 50%.

Finally, there are a number of large scale liquid pool fire studies [17-19] where fire suppression was not the objective. Rather the focus was on studying the burning characteristics and heat transfer processes in large scale pool fires. A recent review by Hamins et al. [17] discussed the structure and energetics of hydrocarbon pool fires with special emphasis on flame height, flame shape and flame pulsation frequency. Koseki and Yumoto [18] investigated the burning characteristics of 2.7m square dike heptane fires with and without open tank fires. The study was motivated by the need to mitigate the dangers of oil storage facility fires. Buch et al. [19] studied the radiative emission fraction of various silicone and organic fuel fires with pool diameter ranging from 0.1m to 1.0m. They showed a correlation between the fuel evaporation flux and the ratio of the heat of combustion and heat of gasification of the various fuels. Ndubizu et al. [20] developed a zone model of a large scale liquid pool fire in the open. They conducted a parametric study of the various input parameters and showed that the heat of combustion is the most critical of the parameters.

In this study, the numerical simulations were carried out with small scale methanol pool fires, while the experiments were conducted with large scale heptane and JP8 pool fires. The objectives are (i) to quantify the effects of the design parameters (e.g., droplet size) on the suppression of a small-scale methanol pool fire (computation) and large scale heptane and JP8 pool fires (experiments); (ii) to compare the major trends observed in the theoretical and experimental results; and (iii) to study the effects of surface cooling mechanism on burning rate in JP8 pool fire.

2.0 THEORETICAL MODEL

The theoretical model considers a small (< 1KW) methanol pool fire. Figure 1 is a schematic of the 2-D (1.0cm wide) pool fire showing the gas phase and liquid phase computational domains as well as some of the physical processes taking place in the gas and liquid phases. Since the flame is assumed symmetrical about the centerline, computation was performed for only 1/2 the domain. The gas phase domain is bounded by the centerline, the inflow boundary, the lateral slipwall boundary and the outflow boundary. Part of the heat generated in the flame is fed back to the fuel surface by radiation, convection and conduction to evaporate the fuel. Heat is also transferred to the liquid through the metal container. The liquid evaporates at a temperature close to the boiling point and the vapor mixes with air and burns in the combustion zone. The resulting hot combustion products entrain the surrounding co-flow air (or air+ suppressant) as they pass through the gas phase domain. Water mist is introduced thoroughly mixed with air through the inflow boundary for base injection, the lateral boundary for side injection and outflow boundary for top injection.

A complete set of unsteady, compressible Navier-Stokes equations for reactive laminar flows are solved in the gas phase to describe the convection of the fuel gases away from the pool surface, diffusion of gases into the surrounding air and the oxidation of the fuel molecules into products. Heat transfer into the liquid pool and the metal container are modeled by solving a modified form of energy equation. Clausius-Clapeyron relations are invoked to model the evaporation rate of the pool of methanol. A two-continuum formulation is used to study the interaction of water mist with the fire. It is assumed that coalescence and break up of droplets within the computational domain are insignificant. A sectional conservation model that is based on dividing the droplet population into sections is used. Each section comprises of droplets of a certain size range and each of the sections is assumed to have its own unique velocity different from that of the gas phase [11]. Momentum conservation equations are formulated for each droplet section and are coupled to those of the gas phase through the drag terms. The governing

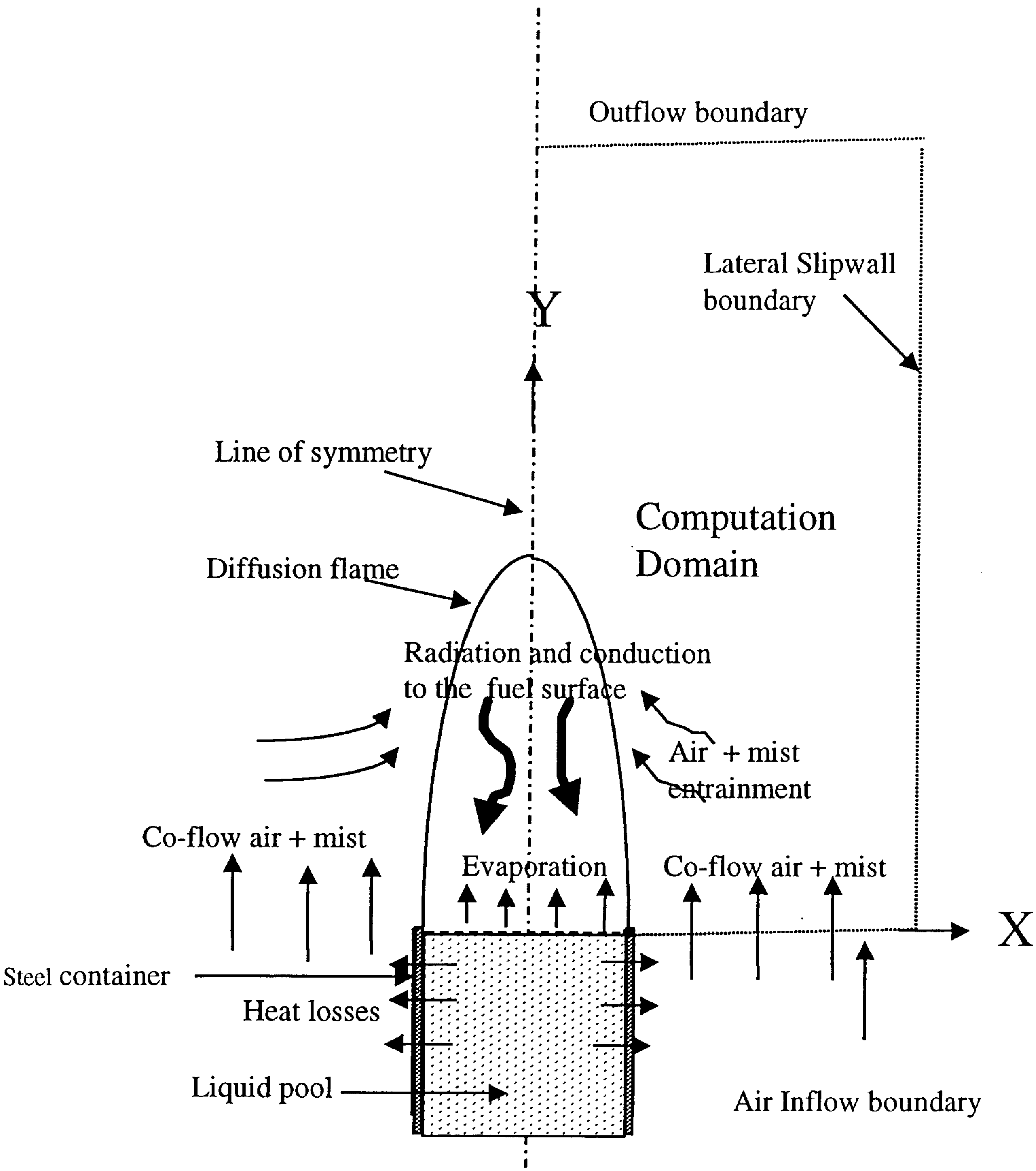

Figure 1: A schematic of the Small Scale Methanol pool fire (Computational Domain bounded by the centerline and the dotted lines)

equations along with appropriate boundary and interface conditions are solved using the Flux Corrected Transport algorithm [21]. The model predicts temperature, species and velocity profiles in the gas phase, the fuel evaporation rate and the integrated total heat release rate. Calculations were made for cases where mist was introduced in base injection, side injection and top injection using various values of droplet size, injection velocity and droplet number density. Details of the model and the parametric study are given in [22,13].

3.0 EXPERIMENTAL

Figure 2 shows a schematic of the setup for the large scale pool fire experiments. The 50 cm diameter pan is connected to the Navy Research Laboratory's self adjusting liquid level apparatus which is described in detail in [23]. A pool of liquid fuel sits on a layer of water at the bottom of the pan. As the fuel burns, the liquid level self adjusting apparatus supplies fuel from the right tank compartment to the pan to keep the pool level constant. This results in a fall in liquid levels both in the left tank compartment and the fuel measuring jar. In the base case tests (no mist addition), the burning rate is obtained directly using the measured drop in liquid level in the fuel measuring jar and the left tank compartment. When mist is introduced some of the droplets go through the flame and enter the liquid pool. Since heptane and JP8 are lighter than water and do not mix with water, the additional water accumulates at the bottom and this tends to push up the level of the fuel in the pool. To address this problem, the self adjusting liquid level apparatus was modified by connecting a second measuring jar to the water in the pan. As the fuel level in the pan changes the water level in the jar changes. By measuring the change in the weight of the water jar the measured burning rate (base case) can be adjusted for the effect of water addition on any changes in the fuel level during the test. The rate of water accumulation in the pan is obtained by measuring the change in water depth after the test using the Kolor Kut ® water finding paste. The Kolor Kut paste is a water soluble paste used in the petroleum industry to measure the water content in a tank of petroleum fuel. The yellow paste is applied evenly on a dip stick. On dipping the stick into a container of fuel and water, the part of the stick in contact with water will turn bright red while the part in contact with fuel will remain yellow. Finally, the burning rate (with mist) is corrected for the effects of mist accumulation in the pan and the equation for burning rate is given by:

$$m = \{625\pi(\Delta h_1) - 25(\Delta W_w) + 12.844(\Delta W_f)\} / \Delta t \qquad \text{where}$$

Δh_1 , ΔW_w and ΔW_f are changes in height of water in the pan, weight of water in the water jar and weight of fuel in the fuel jar, respectively. See the appendix for the details.

The mist delivery system consists of an octagonal nozzle holder which surrounds the pan and can deliver mist at an equal rate from a maximum of eight Bete ® P-series nozzles (see Figure 3). To ensure a constant water flow rate a uniform stream of water is delivered to each nozzle

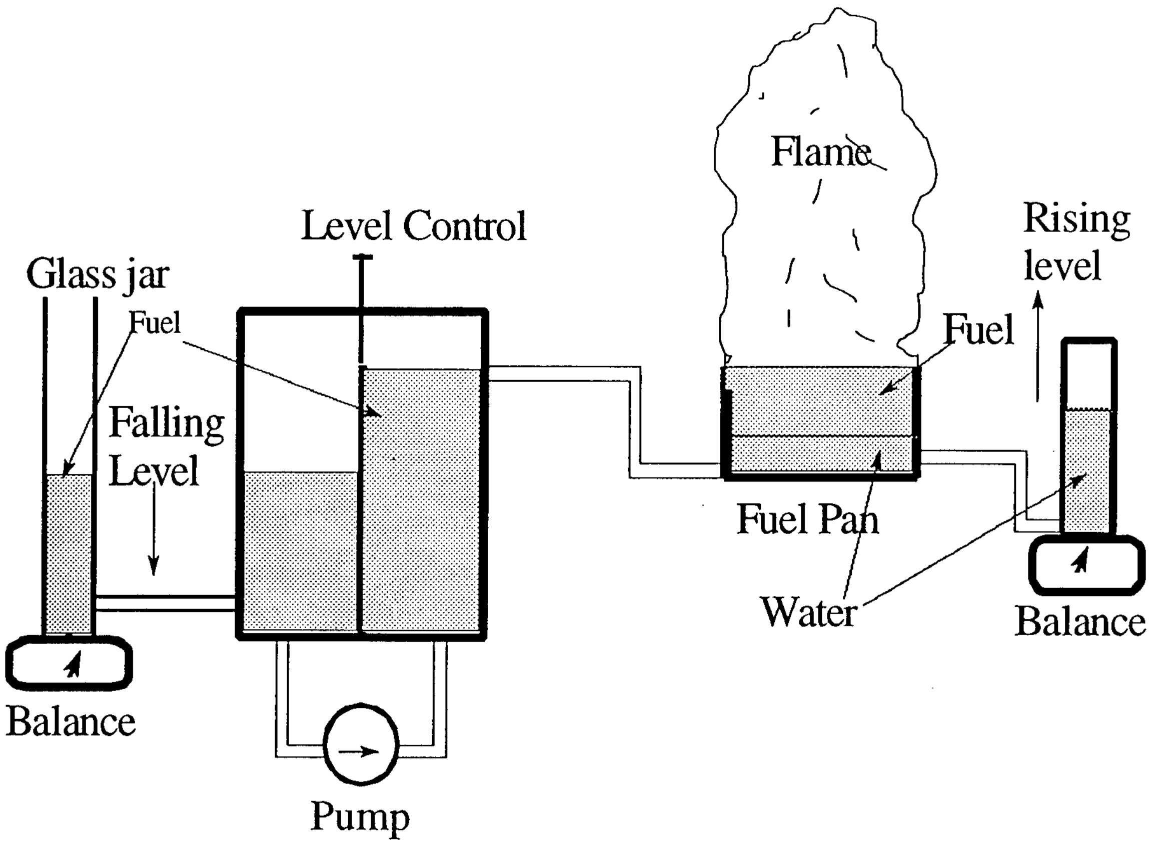

Figure 2: A Schematic of the Experimental Setup for the large scale Liquid Pool fire Tests.

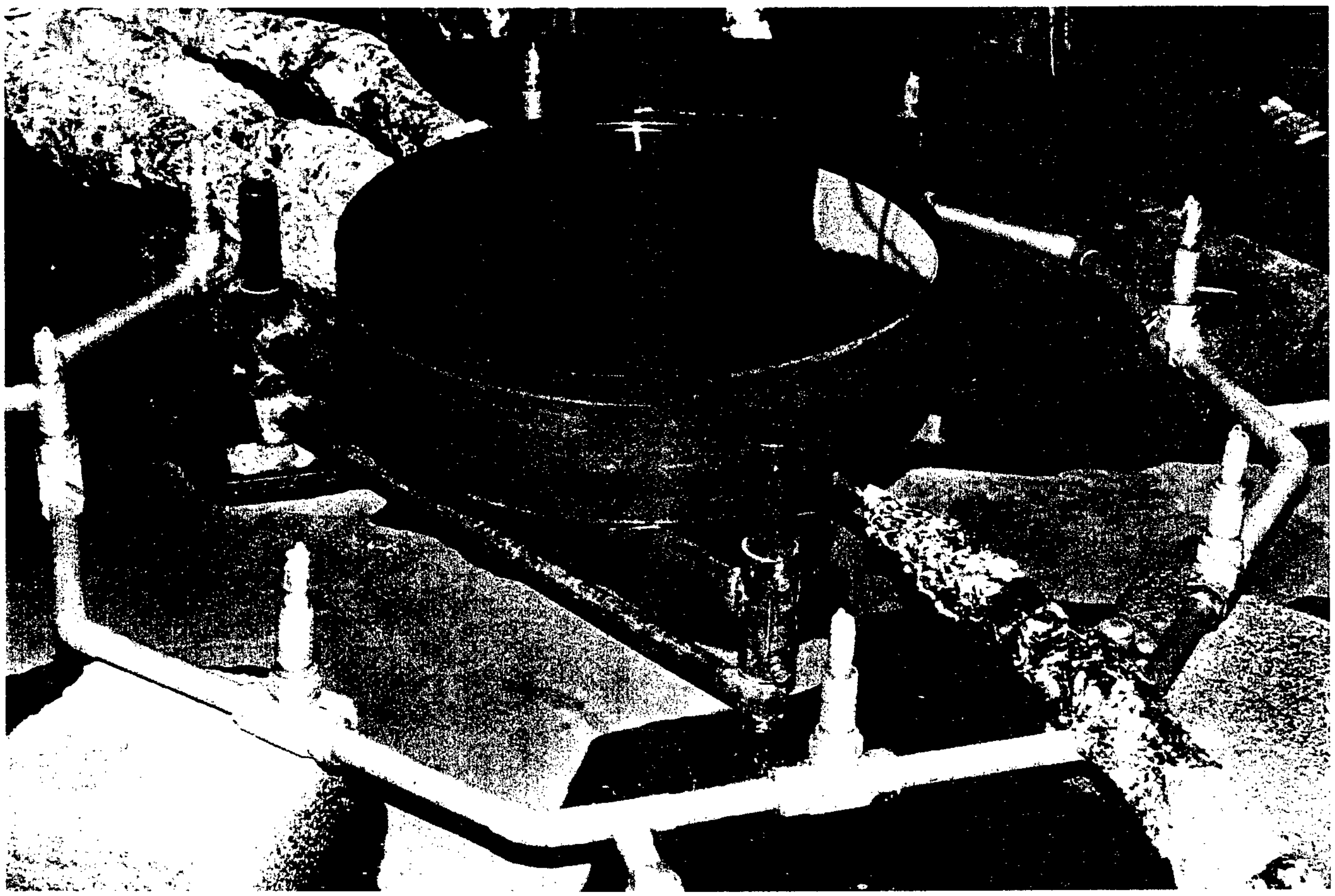

Figure 3: Picture of the Fuel pan and nozzle holder for base Injection

from a nitrogen pressurized water tank. For mist injection from the base the nozzle holder is placed on the floor. For injection from the top the holder is placed at a height of 2.5m with the nozzles pointing downward. This height is about the ceiling height in some of the compartments in the ex-USS *Shadwell* [24].

An array of five K-type thermocouples 25cm apart was used to measure the centerline temperature of the fire. In JP8 tests, a single thermocouple that just touches the surface of the fuel was used to measure the temperature at the center of the fuel surface. Three Medtherm ® model 64-5-20 water cooled total heat flux radiometers were positioned around the fire 75cm from the pan and 120° apart. The signals from the thermocouples and radiometers are received by a National Instruments' SCXI 2000/ SCXI 1200 unit which conditions and digitizes the signals within the fire compartment and sends the digital signals through one cable to the computer. In this way the effect of noise on the signals is minimized. Since the signal from the balance is digital, it is fed directly to the computer.

The experiments were performed in a closed burn-building, 7.6m by 7.0m by 8.0m, with a large opening in the roof to exhaust the combustion products. This considerably reduced the formation of a smoky upper layer. First, the water tank is filled with water and pressurized. The pan is charged with fuel allowing a lip height of 5 - 10mm. This is necessary to avoid fuel flowing over the edge when mist is introduced, since the transfer of water from the pan to the water jar is not instantaneous and the fuel expands as it is heated. Then, the fuel is ignited and after two minutes of preburn, the mist is introduced. Three minutes are allowed for the system to reach a quasi steady state and then the necessary data for calculating the burning rate are taken in the last five minutes. At the end of the five minutes, the fire (or its remains) is extinguished by covering the pan to eliminate the air supply for combustion.

4.0 RESULTS AND DISCUSSIONS

4.1 Water Mist suppression of small scale Methanol pool fire (theory)

A sample result from the numerical simulations is presented in Fig. 4 in terms of suppression in normalized total heat release rate versus the normalized water injection rate. The water flow rates and the heat release rates were normalized with the fuel evaporation rate and the total heat release rate in the base case (no mist), respectively. The normalized total heat release rate is a measure of the degree of suppression where one signifies no suppression and zero signifies extinguishment. Optimum design condition is one that achieves highest suppression with the smallest water flow rate. Hence points closest to the origin represent the most effective conditions while points far away from the origin represent less effective conditions. Figure 4 summarizes the results for 50µm and 150µm droplets, for top injection, base injection at 90° and base injection at 45°. In the 90° base injection the mist flow is in the vertical direction at entry while in the 45° base injection the flow is inclined at 45° toward the flame. The droplet velocity

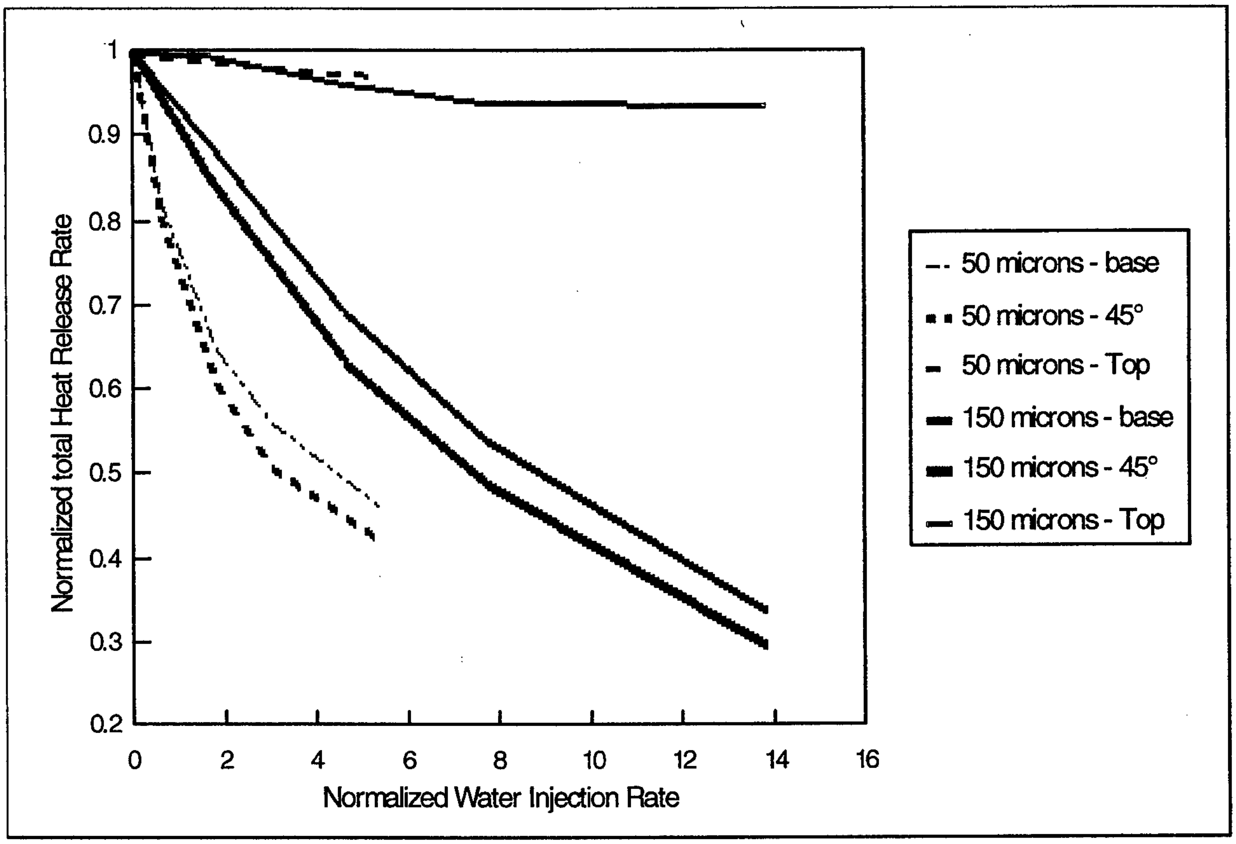

Figure 4: Suppression of Heat release rate versus Normalized mist injection rate for small scale methanol fire (theory)

was 25 cm/sec. in all the simulations and change in water flow rate was obtained by changing the droplet number density. Figure 4 shows that base injection at 45° is the most effective of the three orientations for the 50μm droplets and the 150μm droplets. With base injection (at 90° and 45°) the smaller droplet is more effective than the larger droplet. Very little suppression was obtained with top injection for these two droplet sizes and suppression did not seem to be affected by mist droplet size. However, in some cases (not shown) the larger droplets were more effective than small droplets. In these numerical simulations, the small droplets could have difficulty penetrating both the opposing fire flow and the opposing co-flow air which is necessary in the simulation to stabilize the flame.

4.2 Water Mist Suppression of Burning Rate in Large Scale pool fires (Experiments)

Figures 5 and 6 summarize the experimental results on water mist suppression of burning rate, for large-scale heptane and JP8 pool fires. The suppression in burning rate is plotted against the total mist flow rate normalized with the fuel evaporation rate in the base case (no mist). For the 50-cm diameter heptane base case fire the measured mass evaporation rate is 590 gm/min and this is consistent with the results of Buch et al. [19]. Burning rate is used as a measure of fire severity here, since it is proportional to the chemical heat release rate which has been shown to be unaffected by water addition at conditions far from extinction [7]. The degree of fire suppression is measured by the ratio of the burning rate with mist to that without mist and this ranges between zero (extinguishment) and one (no suppression). The tests were performed with mist of various sizes with sauter mean diameters (SMD) varying between 58μm and 215μm. Mist parameters were not measured in this study but rather they were calculated with formulas obtained from the manufacturer's catalogue. Several tests were repeated and both results are shown in the figure to give an indication of the repeatability of the measurements.

Figure 5 shows the results for heptane pool fire where the red data points (located within water flow > 6 and burning rate ratio > 0.5) are for top injection. The green data points (four points closest to the origin) are for base injection at 45° and the blue data points (the remainder of the data) are for base injection at 90°. One observes that the injection of mist from the base results in higher fire suppression than the injection of mist from the top and that base injection at 45° is the best of the three orientations. A similar trend was observed in Fig. 4 for the small scale methanol fires. It is well known [25,26] that bringing more droplets to the base of the fire will help extinguish it faster. When water mist evaporates at the base of the fire, the residence time of the vapor in the combustion zone is longer, allowing it to mix with the fire gases, dilute oxygen concentration and absorb sensible heat to be heated up to the fire temperature. Thus a full effect of oxygen dilution and sensible heat absorption by the vapor is realized. It is pertinent to recall that the water droplets will absorb 2260J/g of latent heat to evaporate and the vapor absorbs additional 827J/g of sensible heat to be heated up to a fire temperature of say 1200K. This additional sensible heat is due entirely to the difference between the heat capacity of steam and that of air. Thus the effects of heat capacity difference contribute significantly to the overall gas phase cooling as we showed in an earlier paper [27]. On the other hand, when mist is injected from the top, some of the droplets evaporate in the plume region and the water vapor escapes with the flue gases. Hence the effects of oxygen dilution as well as additional sensible heat absorption are not fully utilized.

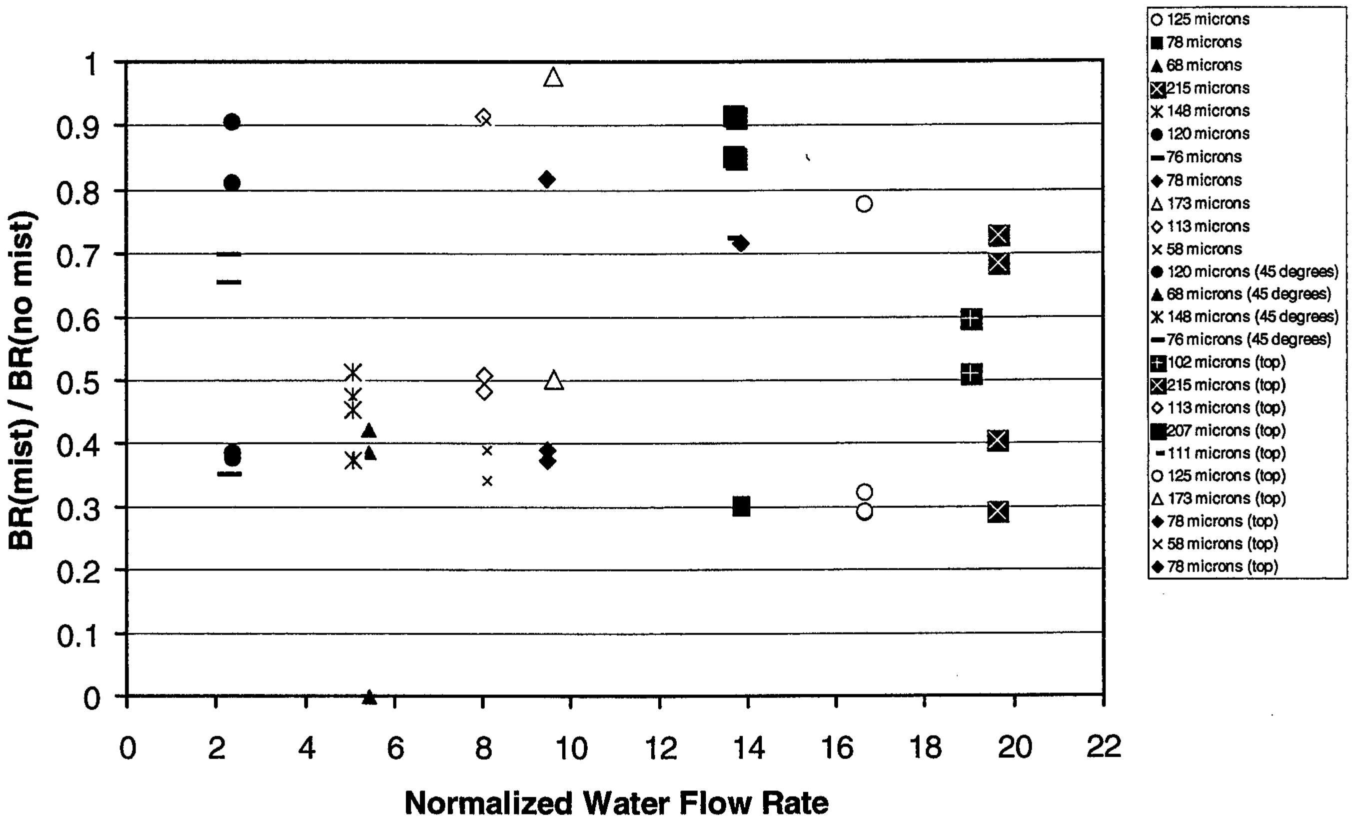

Figure 5: Suppression in Burning rate versus Normalized water flow rate for tests with 50 cm Heptane pool Fire. Mist droplet size varied between 58μm and 215μm. Red data – top injection; Blue – base injection 90° and Green – base injection 45°

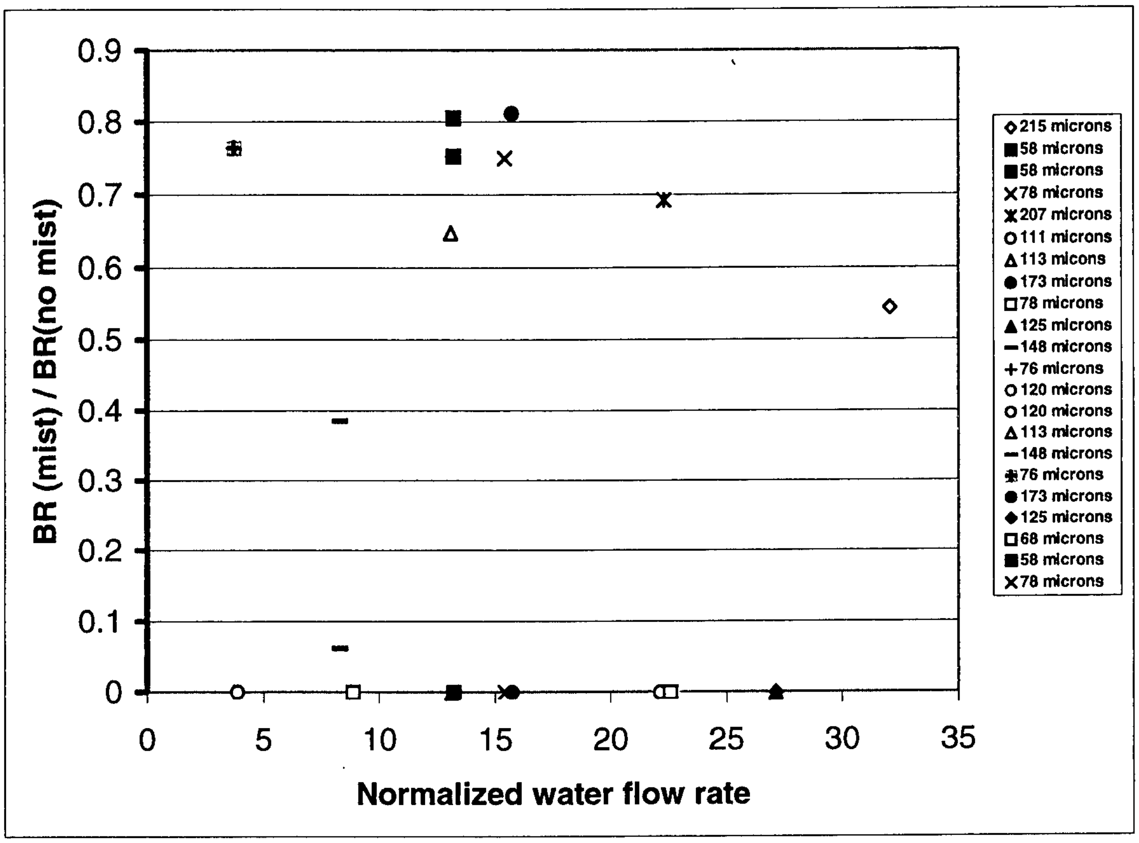

Figure 6: Suppression in Burning rate versus Normalized water flow rate for tests with 50 cm JP8 pool Fire. Mist droplet size varied between 58μm and 215μm. Red data – top injection; Blue – base injection 90° and Green – base injection 45°

Furthermore, Fig. 5 shows that for the same water flow rate, the measured suppression in burning rate in the heptane fire is about doubled in base injection compared to top injection. For example, for the 78μm droplets at a normalized water flow rate of 10, the burning rate ratio is 0.8 in top injection and 0.4 in base injection. The theoretical results for the small scale fire (Fig. 4) show similar substantial difference between the two orientations. However, the difference is not as large for small water injection rates but increases as the water injection rate increases.

In Fig. 5, as the water injection rate increases, the suppression in burning rate increases (burning rate ratio decreases) at a slower rate, especially in tests with base injection. This implies that the "effectiveness" of water decreases as more water is added. For example, with base injection and 78μm droplets we had two data points, at normalized water flow rate about 9 and about 14. Figure 5 shows that when the normalized water flow rate increased from 9 to 14 the burning rate ratio decreased from 0.4 to 0.3 for the base injection test and from 0.8 to 0.7 for the top injection test. A similar trend is observed in Fig. 4 with the small methanol pool fire (theory). Furthermore, in an earlier work with PMMA, Yang et al.[28] found that the fire extinguishment time is inversely related to the water injection rate and that the extinguishment time appears to approach an asymptotic value as the water injection rate goes up. One may speculate that the cause of the observed decrease in effectiveness may be that the entrainment rate drops as the flame is suppressed since the heat release rate goes down. Also the height of the combustion zone goes down with water addition [29] and hence the proportion of the water entrained that will be effective goes down. However, in a related work, McCaffrey [30] studied the suppression of a hydrogen flame where fuel and water spray inlet tubes are concentric such that the spray is totally surrounded by the flame. He also found that the effectiveness of the water in suppressing fire temperature decreased as more water was added. There was no information as to whether the water was not totally consumed during every test.

The effects of droplet size on the suppression of burning rate is also shown in Fig 5. It shows that at the same water flow rate small droplets are more effective than large droplets in all three orientations. For example, at the normalized water flow rate of 10 the burning rate ratio with the 78μm droplets (top injection) is about 0.8 but with 173μm the ratio is nearly 1.0. The difference in effectiveness seems to be more in top injection than in base injection. This may have to do with the way the Bete nozzle 90° sprays reach the flame. Because of the large spray angle, a substantial part of the mist flow stream may be inclined toward the flame rather than flowing parallel to it. More of the droplets in the inclined stream will reach the base of the flame easier in the base injection scenario than in the top injection scenario. The theoretical results in Fig. 4, however, show no substantial difference in the effectiveness of the large and small droplets for top injection. In the experiments, the flow of fire gases opposes the downward mist flow and one will expect the larger droplets to have a greater chance of penetrating this flow since they may have higher momentum. However, an estimate of the typical spray thrusts at the nozzle exit, for the conditions in our experiments, range between 1.1N and 0.2N (see Table 1). On the other hand, the plume thrust at the nozzle position estimated with Heskestad's correlation [31] is about 10N for heptane pool fire with top injection. Hence the plume-to-spray thrust ratio is of the order 10-

.**Table 1: Calculated spray thrust at nozzle exit for a sample of nozzles used in the tests (mist parameters calculated with formulas from the manufacturers catalogue)**

Droplet SMD (μm)	Flow rate (lpm)	Exit velocity (m/s)	Thrust (N)
125	2.46	27.8	1.1
215	2.89	13.2	0.63
58	0.6	34.2	0.34
68	0.4	40.7	0.27
78	1.02	26	0.44
111	2.0	25.4	.85
173	1.42	16	0.38

50 at the nozzle exit. This ratio is higher than that reported in the work of Downie et al. [15]. They showed that at a plume-to-spray thrust ratio of 5-10 there was little penetration of droplets coming from the top into the fire region. Therefore mist droplet penetration of the fire plume from the top is expected to be very low in these tests and that is why the large droplets are not more effective than the small droplets. Furthermore, the fire is surrounded by mist and there are streams of droplets outside the range of the fire flow. These droplets reach near the fire base from where they are entrained into the fire with the surrounding air. The smaller droplets which attain their terminal velocity faster, have a better chance of being entrained into the fire. The current results indicate that in the tests with top injection, the droplets entrained from the side contributed more to the suppression of the fire than the droplets that penetrated through the opposing fire flow.

Figure 6 presents a similar result for suppression of burning rate in JP8 pool fires. The fire was extinguished in three of the tests with top injection. These data are shown on the X axis between 20 and 25. The group of data located at water injection rate greater than 10 and burning rate ratio greater than 0.5 are for top injection. All the data for top injection are shown in red. The three data points closest to the origin are for base injection at 45°. They are shown in green. The rest of the data are for base injection at 90° and they are shown in blue.

Figure 6 shows similar trends observed in heptane pool fire tests (Fig. 5) and theoretical predictions with small scale methanol fire (Fig. 4). These trends are. First, water mist is more effective in suppressing the fire with base injection where droplets are brought close to the fire base than with top injection. Secondly, smaller droplets are more effective than large droplets in every injection orientation. This similarity is an indication that the results of the parametric study conducted with a small scale laminar pool fire are useful in the design of water mist suppression systems for large scale fires.

However, there are some interesting differences between the results with heptane and those with JP8. First, the suppression in burning rate was generally more in the JP8 tests than in the heptane tests for the same experimental conditions. For example, in the test with the 215μm droplets the burning rate ratio in the heptane fire, top injection, was about 0.7, while the same ratio for JP8 fire was about 0.5. Furthermore, the fire was extinguished in most of the JP8 fire tests especially those with base injection. Meanwhile, fire extinguishment was obtained only in one test (68μm, base injection 45°) with heptane.

The greater suppression achieved with water mist in JP8 fires compared to heptane fires can be attributed to many factors and a key significant factor is the direct cooling of the fuel surface by water droplets (surface cooling mechanism). In the heptane fires mainly gas phase cooling and oxygen dilution bring about suppression. This is because the boiling point of heptane is about 98°C and very little droplet evaporation is expected to take place at the fuel surface for the droplets that reach the surface. In an earlier work we had shown that the role of surface cooling mechanism is insignificant in methanol pool fires where the boiling point of the fuel is less than that of water [29]. With JP8, boiling starts at about 160°C and a larger fraction of the fuel boils at temperatures above 200°C. Since the surface temperature is that high, more of the water droplets that reach the fuel surface can absorb latent heat and evaporate there. Indeed, it was observed that the injection of water into a JP8 fire produced glowing spots on the fuel surface and a cracking sound similar to that produced when water is sprayed into hot oil. This is similar to the microexplosion phenomena observed in water-in-oil emulsion droplet combustion. Earlier workers [e.g., 32-34] found that when water microdrops are surrounded by oil of sufficiently higher boiling point compared to that of water, then the microdroplets can be superheated by the suppression of vaporization by the oil. Microexplosion can occur once the water temperature exceeds the limit of superheat. What we observed in the JP8 tests suggests that microexplosion took place when water droplets were superheated by the surrounding JP8 at a temperature much higher than 100°C. A similar effect was not observed when water was injected into heptane fires.

It is difficult to measure the liquid-gas interface temperature accurately. However, the temperature we measured in the neighborhood of the fuel interface (thermocouple just touched the liquid) in the JP8 pool fires showed a significant drop when mist was introduced. For example, Fig. 7 is a typical plot of surface temperature versus time for a base case test (no mist) and a test where mist was injected from the top. Mist injection started after two minutes and Fig. 7 shows that about a 100°C temperature drop was obtained when the mist was injected. The drop in surface temperature was normalized and plotted against the suppression in burning rate in Fig. 8. A straight line was drawn to show the trend of the data. Figure 8 shows a correlation between the drop in surface temperature and the suppression in burning rate. As the drop in surface temperature increases the suppression in burning rate increases (normalized burning rate decreases). The temperature data in Figs. 7 and 8 as well as the observed microexplosion phenomena strongly suggest that the addition of water mist has a direct effect on the cooling of the fuel surface in JP8 pool fire tests.

4.3 Water mist Suppression of fire temperature and total heat flux (Experiments)

The introduction of water spray into a pool fire results in the lowering of flame height as well as flame temperature [35,27]. Figure 9 is a picture of a base case heptane fire (on the left) and the same fire when mist was injected (on the right). The flame became shorter

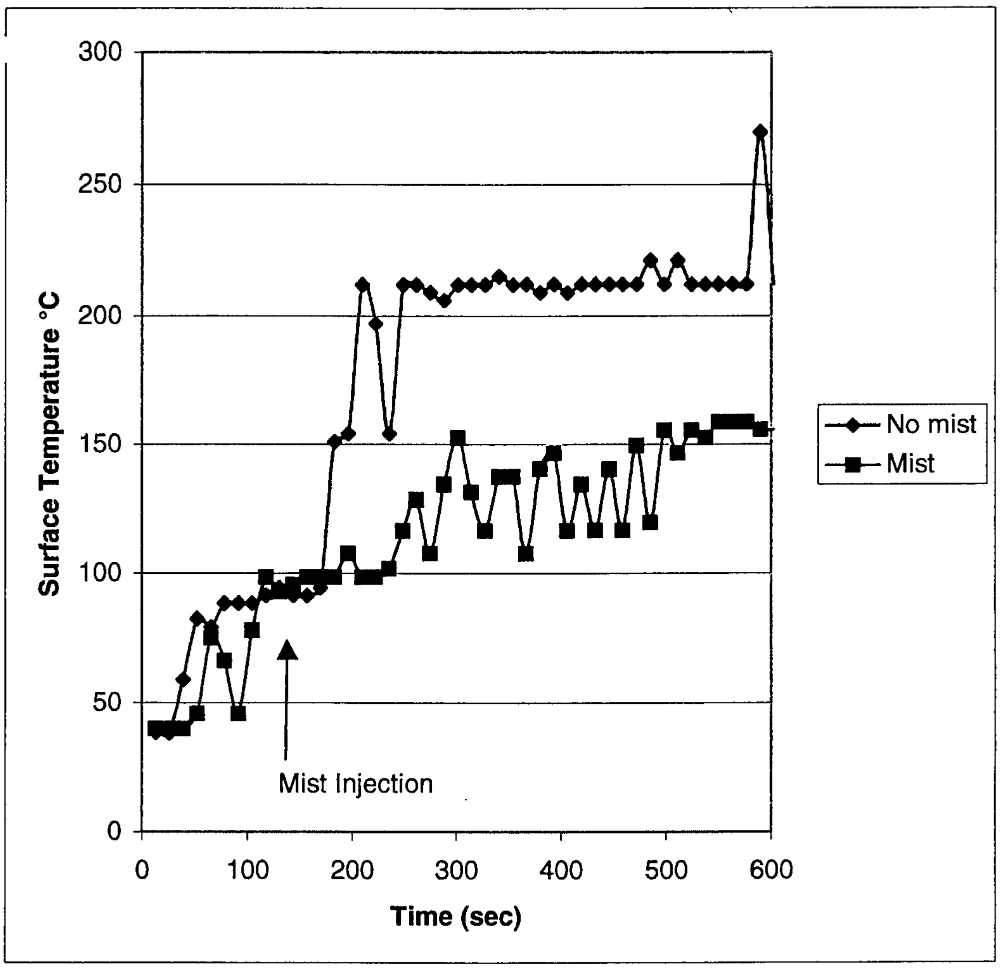

Figure 7: Effects of water addition on fuel surface temperature in the JP8 pool fire. Top injection, droplet sauter mean diameter = 173μm

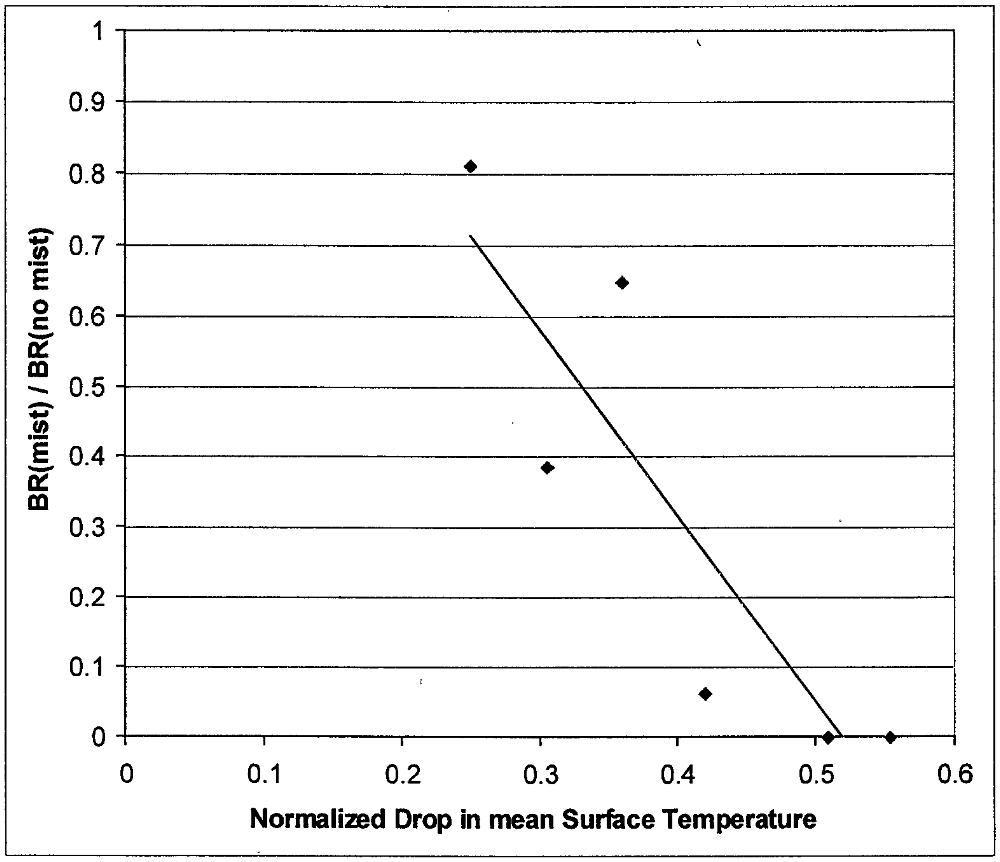

Figure 8: Suppression in burning rate of JP8 pool fires versus normalized drop in mean fuel surface temperature.

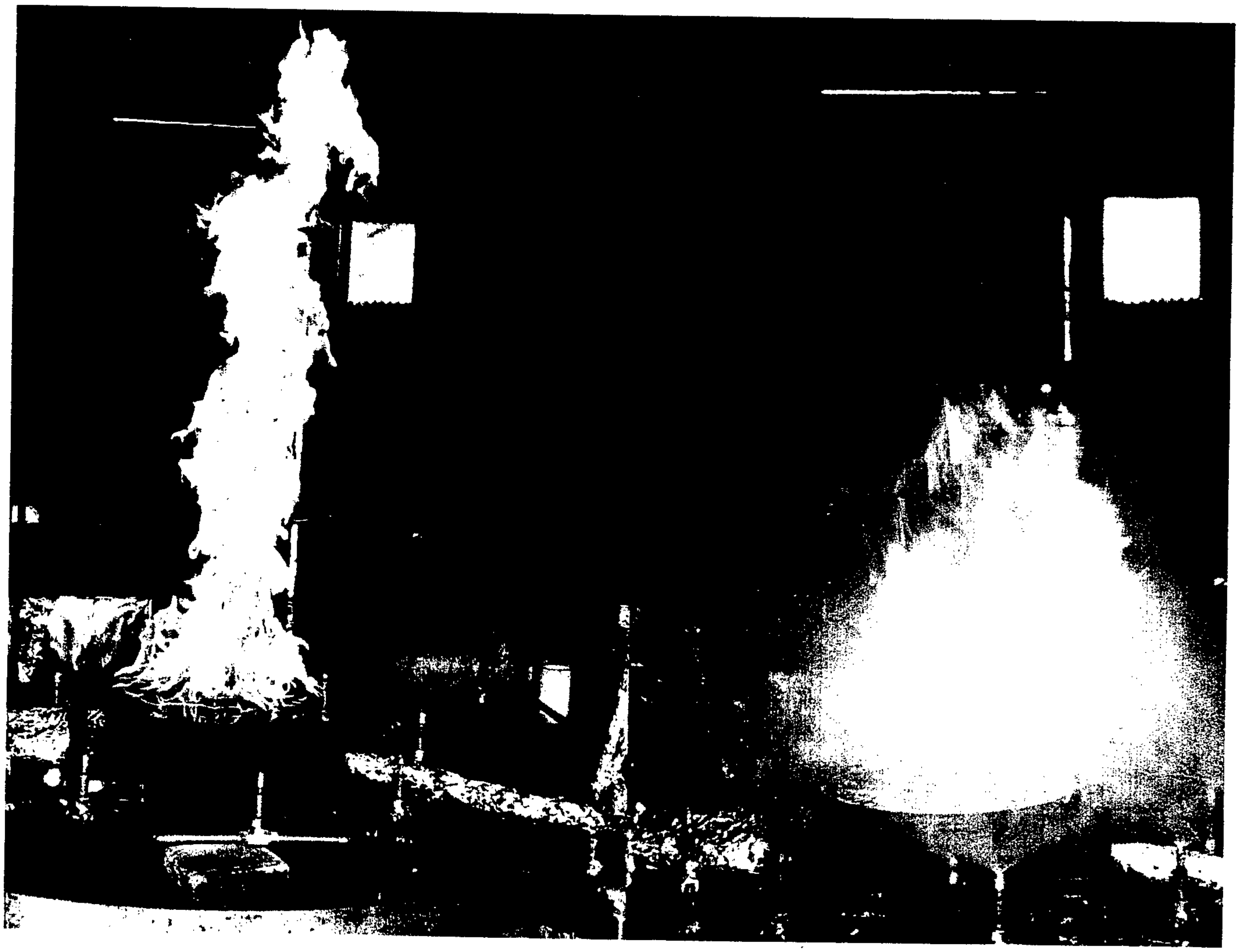

Figure 9: Picture of a heptane pool fire with no mist (left) and mist, base Injection (right)

when mist was introduced. Figure 10 shows the fire centerline temperatures measured in two tests at the same total water flow rate. In Fig. 10a the SMD of the droplets is 68μm while in Fig. 10b it is 148μm. In each case water was injected from the top. T_0 was measured by the thermocouple nearest to the fuel surface (about 20cm above the fuel surface) while T_5 was measured by the thermocouple farthest above the surface (about 120cm above the fuel surface). There is a bigger drop in temperature after water mist was introduced in the test with smaller droplets (Fig. 10a) than in the test with large droplets. In fact, T_0 hardly dropped in the test with larger droplets. Since droplet evaporation is inversely proportional to the droplet diameter, droplet size will affect the suppression in fire temperature such that smaller droplets are more effective than large droplets.

For the various tests with heptane fire, the measured centerline temperature at each height above the liquid pool was averaged over the last five minutes of the test. Recall that the burning rate data were taken within this time. The average temperatures T_0 and T_5 are plotted against normalized mist flow rate in Figs. 11a and 11b, respectively. These plots show a lot of scatter as one would expect for this scale of measurement. Figure 11a shows that T_0 did not vary much between top injection and base injection. The position of the thermocouple is such that mist droplets can hardly get close to it whether by penetrating through the opposing fire flow or by being entrained from below. Figure 11b shows a greater scatter than Fig. 11a. However, the data for base injection and top injection are separated. One can decipher from Fig. 11b that T_5 is generally lower for base injection than for top injection. This observation is consistent with our earlier conclusion that in the top injection tests, mist droplets find it difficult to penetrate the opposing fire flow. This is because of the high plume-to-spray thrust ratio. If the droplets could easily penetrate the opposing fire flow, T_5 would not have been higher in top injection than in base injection since the thermocouple is about half way between the two nozzle positions. The mist droplet sizes are written next to some of the data points. Again, by comparing the data at a given water flow rate, one observes that smaller droplets are more effective in suppressing the fire temperature in both figures.

Finally, the effects of droplet size on measured total heat flux are shown in Fig. 12. A typical radiometer output is shown for heptane tests where the water flow rates were the same but the SMD of the droplets were 215 μm and 102μm, respectively. With the smaller droplets the drop in heat output when water was injected was about 60% while with the larger droplets the drop was about 20%.

5.0 CONCLUSIONS

This report has presented the results of a theoretical and experimental parametric study of water mist suppression of liquid pool fires. The numerical study was conducted with a small scale 2-D methanol pool fire. A typical result was presented for droplet SMD of 50μm and 150μm with mist injection from the top, base at 90° and base at 45°.

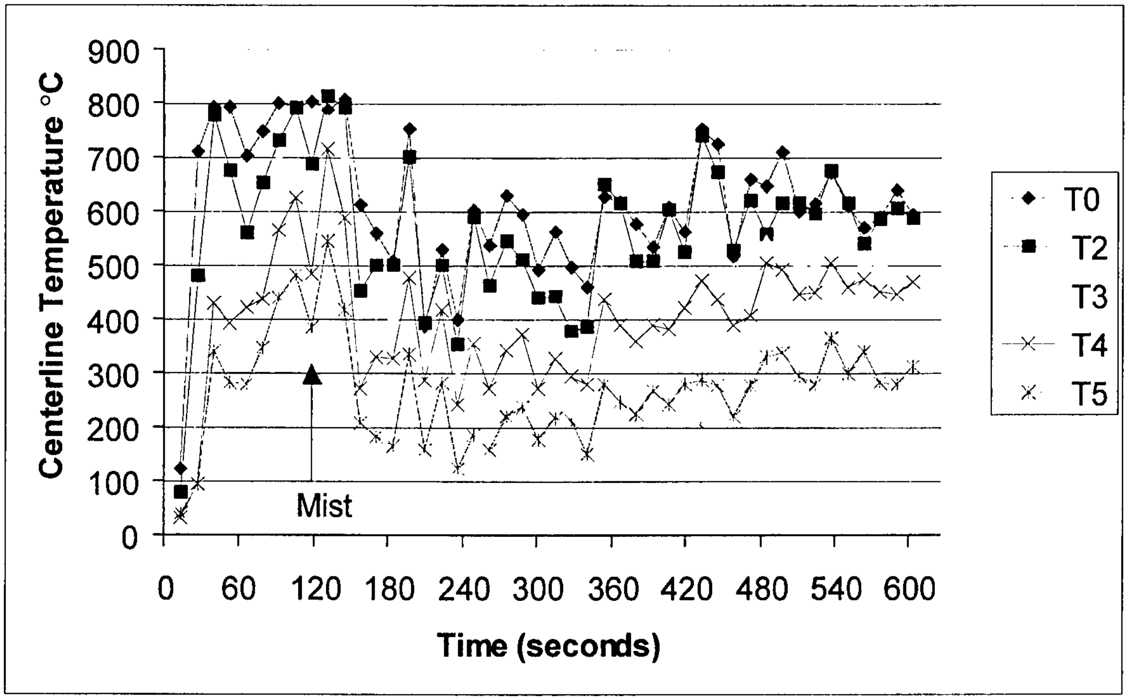

Figure 10a: Effects of droplet size on fire centerline temperature. Heptane pool fire with water injection from the base. T_0 and T_5 are the thermocouples nearest and farthest from the fuel surface, respectively. Droplet size = 68μm.

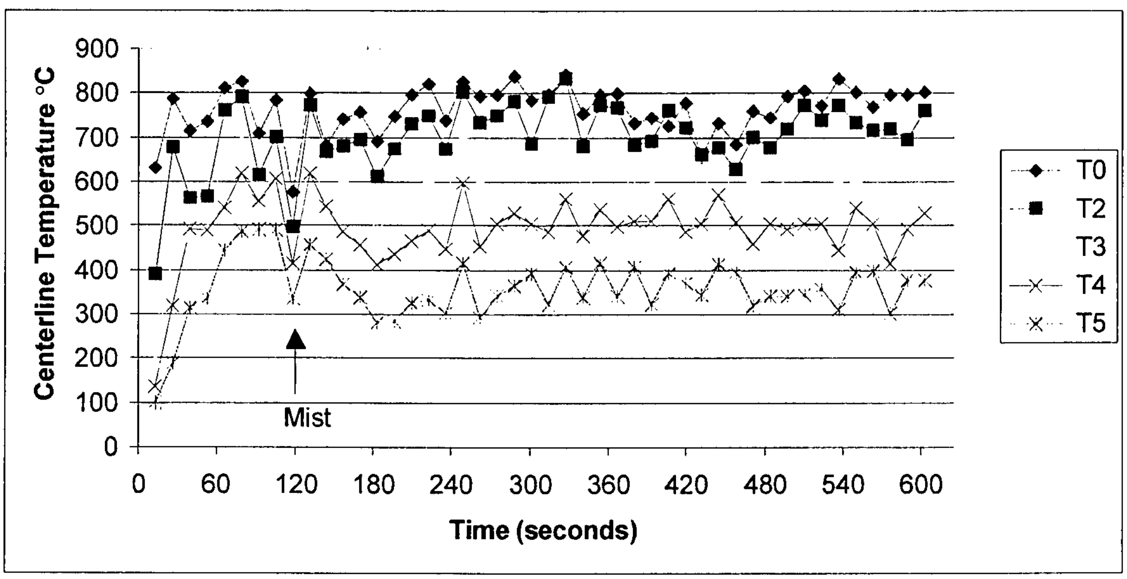

Figure 10b: Effects of droplet size on fire centerline temperature. Heptane pool fire with water injection from the base. T_0 and T_5 are the thermocouples nearest and farthest from the fuel surface, respectively. Droplet size = 148μm.

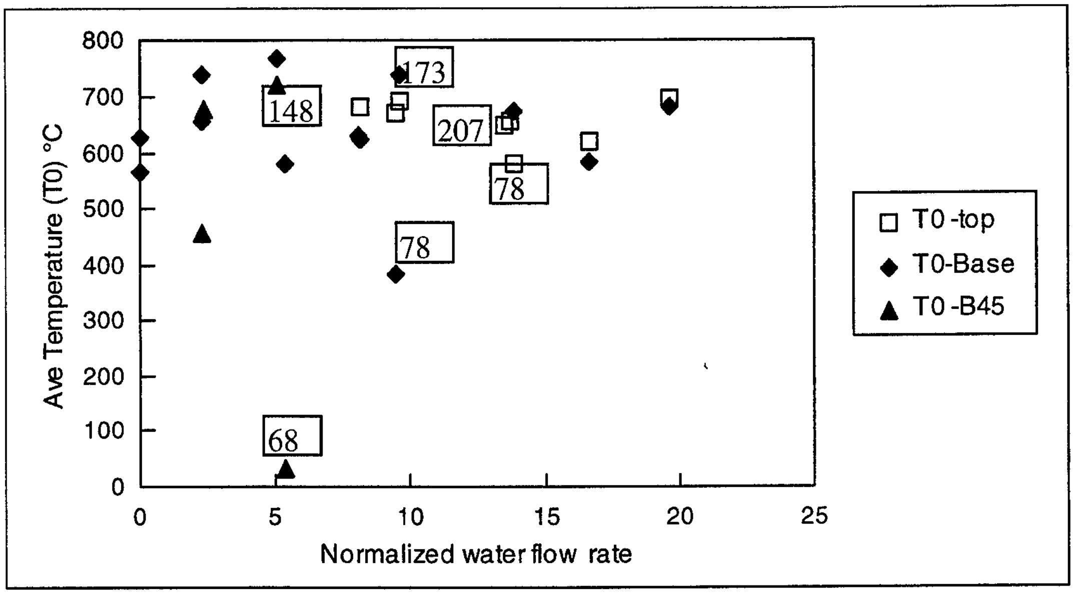

Figure 11a: The effects of Injection orientation and droplet size on the average centerline temperature, T_0 (about 20 cm from fuel surface).

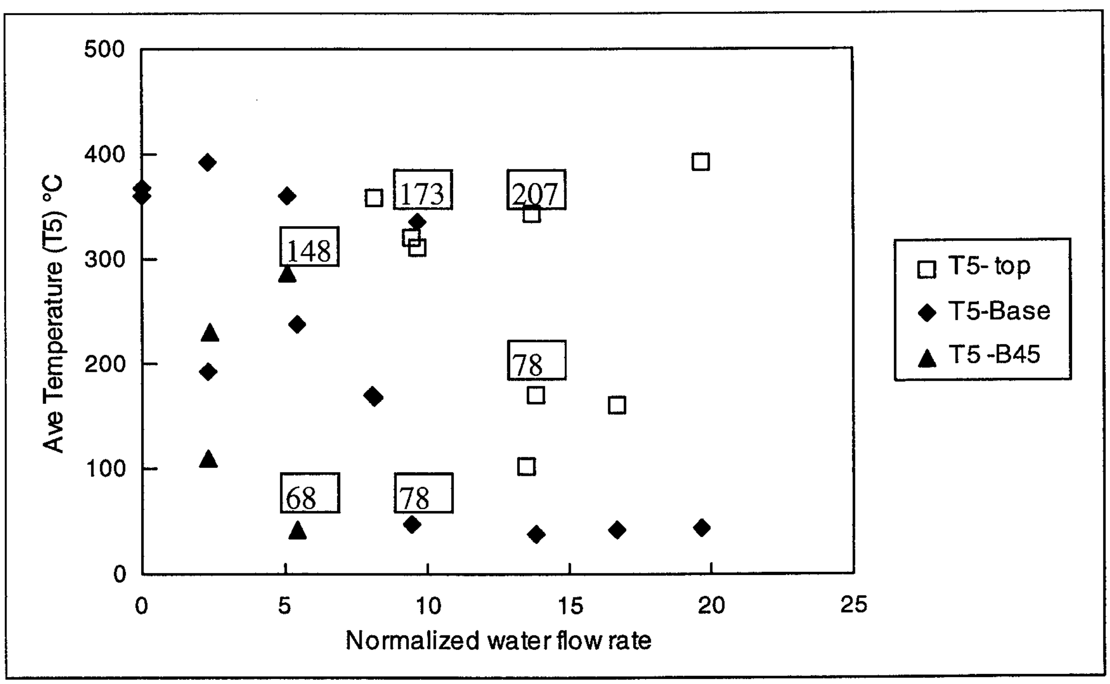

Figure 11b:The effects of Injection orientation and droplet size on the average centerline temperature, T_5 (about 120 cm from fuel surface).

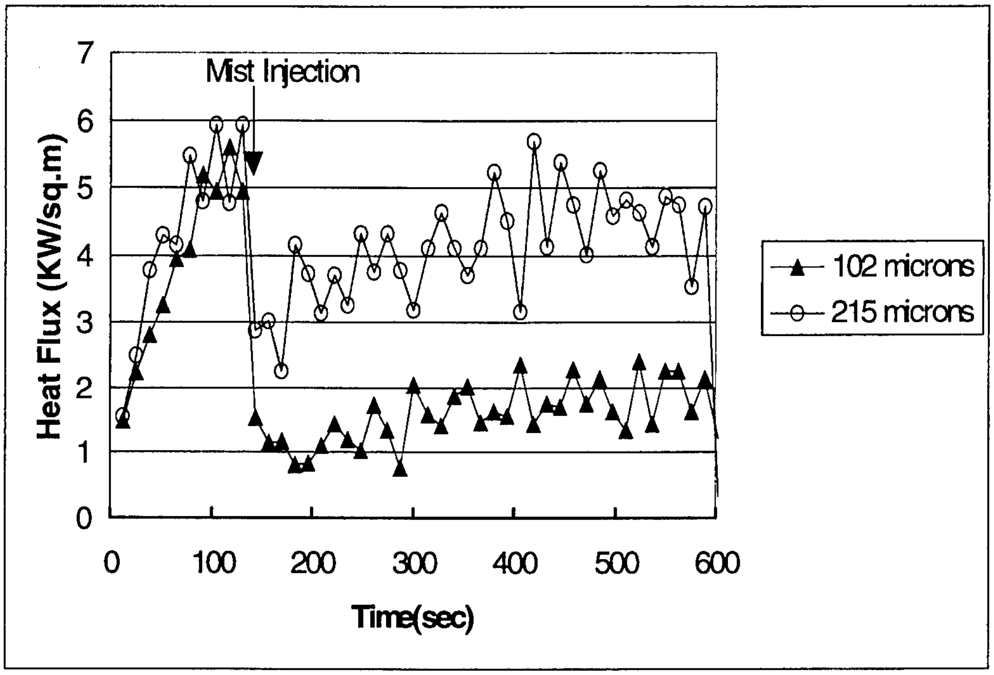

Figure 12: Effects of droplet size on measured heat flux for a heptane pool fire with mist injection from the top.

Experiments were conducted with large scale heptane and JP8 pool fires where mist was injected from the base and top like in the numerical simulation. Droplet size was varied between 58μm and 215μm. Burning rate and fire centerline temperatures were measured for tests with and without mist. Analysis of the results of theoretical parametric study (small scale) and experimental data (large scale) lead to similar conclusions. First, the results show that base injection of droplets enhanced their suppression effectiveness by as much as two times compared to top injection. This is because when droplets evaporate within the lower region of the fire, a greater effect of oxygen dilution and sensible heat absorption is realized. Secondly, smaller droplets are more effective than larger droplets in fire suppression both in top and base injections. In the experiments with top injection, the plume-to-spray thrust ratio is high and hence droplets have difficulty penetrating the opposing fire flow. This suggests that in these tests, the droplets entrained from the side of the fire played a key role in the fire suppression rather than the droplets that penetrated through the opposing fire flow. The similarity between the model predictions and the experimental data indicates that the results of the parametric study conducted with a small scale laminar pool fire, can be useful in the design of water mist suppression systems for large scale fires.

Finally, the experimental results show that water mist was more effective in suppressing the JP8 fire than the heptane fire. It is concluded that this is largely due to the additional effects of surface cooling because of the following reasons: (i) the addition of water mist into a JP8 fire resulted in a burning with cracking sound and the presence of glowing spots on the fuel surface (microexplosion phenomena [32-34]); and (ii) the suppression in burning rate was shown to correlate with the drop in fuel surface temperature in the JP8 fires.

6.0 ACKNOWLEDGMENT

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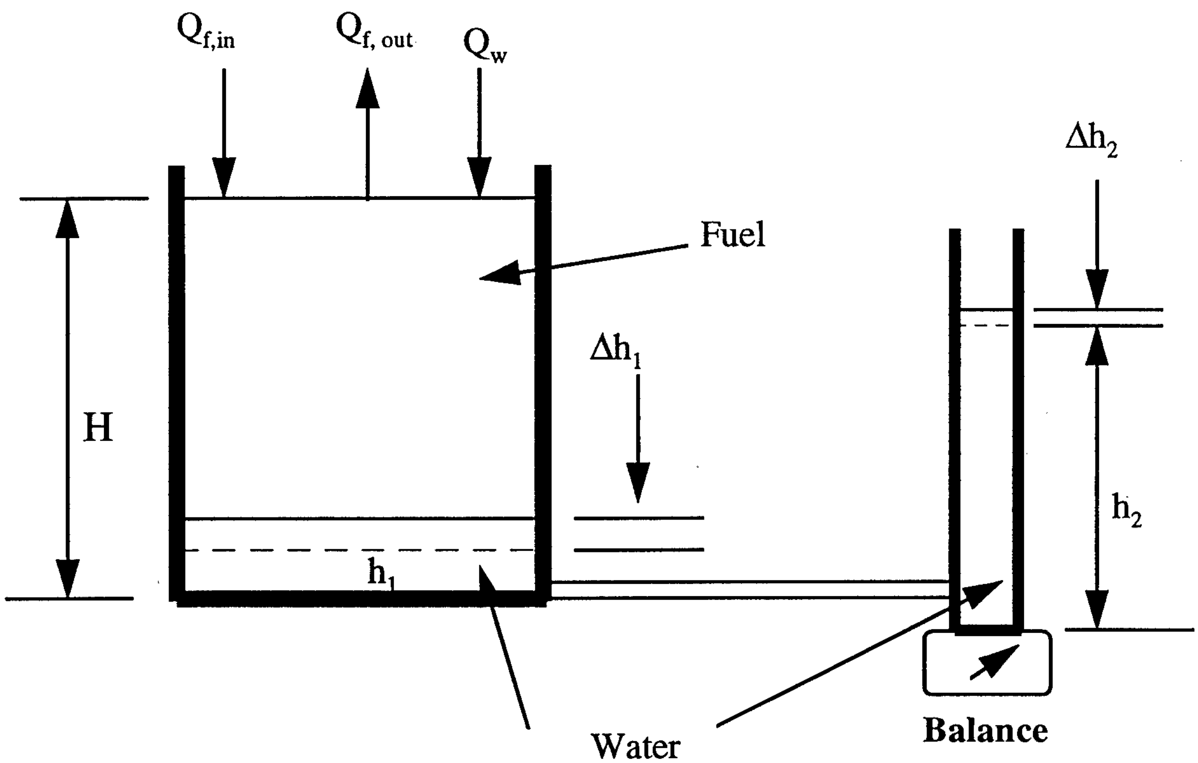
APPENDIX

Derivation of the Burning Rate Equation in Tests where Mist was introduced.



Initially, the pan is filled with water and fuel with the overall liquid height, H and the height of water level, h_1. The height of the water level in the water jar is h_2 . Pressure balance between the pan and water jar gives;

$$h_1\rho_w + (H_1 - h_1)\rho_f = h_2\rho_w \qquad (1)$$

where ρ_f and ρ_w are the densities of fuel and water, respectively.

Within the time Δt minutes when data are taken the volume of fuel that evaporated is $Q_{fl,out}$ cm^3, while the volume replenished from the tank is $Q_{fl,\,in}$ cm^3 . At the same time Q_w cm^3 of water entered the pan in form of mist and the volume of liquid in the pan changed by ΔQ cm^3 . Since water and fuel are incompressible;

$$Q_{fl,out} = Q_{fl\ in} + Q_w - \Delta Q;$$

$$= [\Delta W_f\,(12.844)]/\rho_f + \pi(d^2/2)[\Delta h_1 - \Delta H] \qquad (2)$$

where;

ΔW_f = change in weight of the fuel jar (not shown)

d = diameter of the pan

Δh_1 = change in the height of the water level in the pan

ΔH = change in the overall liquid height in the pan.

The cross -sectional area ratio between the fuel jar and left compartment of the fuel tank is 12.844. See figure 2.

After the test time Δt, the pressure balance between the pan and the water jar is;

$$[H2 - (h1 + \Delta h1)]\,\rho_h + (h1 + \Delta h1)\rho_w = (h2 + \Delta h2)\rho_w \qquad (3)$$

From (1) and (3):

$$\Delta H = H2 - H1 = [\Delta h2\rho_w - \Delta h1(\rho_w - \rho_h)]/\rho_h = [\Delta h2 - \Delta h1(0.32)]/0.68$$

$$(\Delta h_1 - \Delta H) = (\Delta h1 - \Delta h2)/0.68; \qquad (4)$$

where;

$\Delta h2 = \Delta W_w/A_j$, is the change in height in the water jar. A_j is the cross-sectional area of the water jar and ΔW_w is the change in the weight of the water jar.

Burning Rate, $m = (Q_{fl,out}\,\rho_f)/\Delta t$; and substituting eq. (4) into eq. (2) for the pan diameter of 25 cm and water jar diameter of 5 cm we obtain,

$$m = [625\pi(\Delta h1) - 25(\Delta W_W) + 12.844(\Delta W_f)]/\Delta t. \qquad (5)$$